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IN SEARCH OF EMERGING MAGNETIC FLUX UNDERNEATH THE SOLAR SURFACE WITH ACOUSTIC IMAGING

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ABSTRACT

With the method of acoustic imaging in helioseismology, we study an emerging flux region, NOAA 7978, using data taken with instruments of the Taiwan Oscillation Network (TON) and the Michelson Doppler Imager (MDI). Phase-shift maps of NOAA 7978 focusing at different depths are constructed, which show the evolution of emerging magnetic flux. Although the emerging flux below the solar surface is not easy to be directly recognized in the phase-shift maps, average phase shifts over the active region reveal the signature of upward-moving magnetic flux in the solar interior. The average phase shifts in the interior normalized to their surface values are larger at earlier times in both the TON and the MDI data. This suggests that the flux below the surface is moving upward during the development of the active region.

Subject headings: Sun: magnetic fields — Sun: oscillations — sunspots

1. INTRODUCTION

Acoustic imaging in helioseismology (or helioseismic holography) is a method for reconstructing acoustic signals in the solar interior by coherently adding acoustic signals observed at the solar surface based on a time-distance relation (Chang et al. 1997; Braun et al. 1998; Chen et al. 1998; Chou et al. 1999). Using data taken with the Taiwan Oscillation Network (TON), we have shown that this method successfully reveals absorption and phase-shift features of solar magnetic regions (Chang et al. 1997; Chen et al. 1998; Chou et al. 1999). It has been long proposed, formulated, and simulated that the formation of solar magnetic regions is due to magnetic flux rising up through the solar convection zone. However, among applications of acoustic imaging, an attempt using TON data to image emerging magnetic flux before it appears at the surface gave a negative result (Chou et al. 1998). In that study, no acoustic feature was detected in absorption and phase-shift maps at depths down to 80 Mm. This leads to two speculations. (1) The acoustic absorption and phase shift in magnetic regions occur only at a layer very close to the surface. All features in absorption maps and phase-shift maps of the solar interior constructed with the technique of acoustic imaging are due to the poor vertical resolution. (2) The upward-moving velocity of magnetic flux is higher than several hundred meters per second.

In this Letter, we report results of a more extensive study of searching for emerging flux below the surface. We use the data taken with the TON instruments (Chou et al. 1995) and the Michelson Doppler Imager (MDI) on board the *Solar and Heliospheric Observatory* (Scherrer 1995). Our results show the signature of upward-moving magnetic flux through the solar interior, which rules out the first speculation mentioned above.

2. DATA ANALYSIS AND METHODS

The emerging flux region NOAA 7978 first appeared at the surface at about UT 17:00 on 1996 July 6 in MDI magnetograms. It continued to develop into a large active region in the next 3 days, reaching the maximum around July 9. The interval of the TON data used here is 1996 July 6–9 and for the MDI data is 1996 July 5–10. TON data are 1080 × 1080 pixel full-disk images, and MDI data are 1024 × 1024, both with a cadence of 1 minute. The average TON K-line images of the selected target region, which includes NOAA 7978, are shown in Figure 1. The dimension of the target region is about 21° (255 Mm) in longitude and 13° (158 Mm) in latitude.

Data are filtered with a Gaussian filter centered at 3 and 5 mHz, both with a FWHM of 1 mHz. The acoustic aperture used in this study is an annular region of 4°–14°. When focusing at the surface, this collecting area corresponds to p-mode waves from $l \approx 110$ to $l \approx 260$ at 3 mHz, and lower for focusing at some depth.

By correlating two acoustic-signal time series at a focal point constructed with ingoing and outgoing waves, the phase shift can be determined (Chen et al. 1998). Phase shifts have proven more sensitive than absorptions to magnetic fields. In this study, we construct phase-shift maps of the target region focusing at various depths down to 40 Mm and in a time sequence spanning from 1996 July 5 to July 10. Technical details of constructing phase-shift maps and data reduction in acoustic imaging are discussed in Chen et al. (1998) and Chou et al. (1999). The MDI data preparation for acoustic imaging is discussed in Chou & Duvall (1999).

Data are divided into segments of 512 frames to construct phase-shift maps. These phase-shift maps with 8 hr temporal resolution show phase-shift features in the active region. But the signal-to-noise ratio (S/N) is low for earlier days when magnetic fields are weak and for maps focusing at deeper layers. Six consecutive phase-shift maps (2 days) are averaged to improve the S/N. The same procedure is carried out for both TON and MDI data at 3 and 5 mHz. Two day running-average phase-shift maps from MDI data at 3 mHz are shown in Figure 2. The other three sets of maps (from MDI data at 5 mHz and from TON data at 3 and 5 mHz) show similar behaviors, except that the phase shift in magnetic regions is larger in 5 mHz maps than in 3 mHz ones (see also Fig. 3).

Features in surface phase-shifts maps correlate well with magnetic features shown in the average K-line images. These phase-shift features are also visible down to some depth. We are searching for subsurface features at the location of the emerging flux region before the flux appears at the surface.

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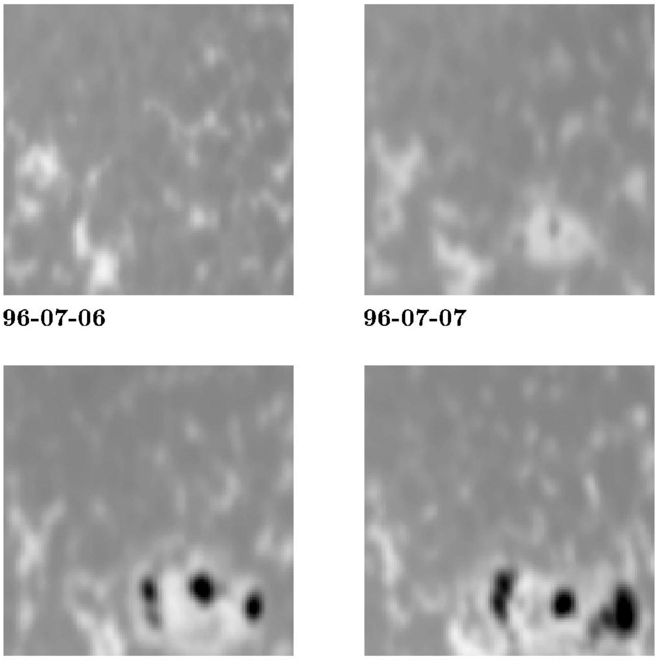

FIG. 1.—K-line images of the selected target region, which includes NOAA 7978 at its lower right corner. These images are the averages in the interval of UT 9:00 to 17:00 on each day.

The phase-shift maps in the first column of Figure 2 are constructed with a 2048 minute time series before the flux appears at the surface. Thus, the noise is smaller than that of other maps in Figure 2. The phase map at 30 Mm depth shows a weak feature at the location of the emerging flux region, while there is no corresponding feature at the same location at the surface and other depths. To confirm this feature at 30 Mm depth, we use other smaller and larger acoustic apertures to construct phase-shift maps. In these phase-shift maps, no feature is visible at this location at any depth from the surface to 40 Mm. Therefore, at this stage we cannot confirm that the feature shown at 30 Mm depth in the first column of Figure 2 corresponds to the emerging magnetic flux below the surface.

To investigate the depth dependence and evolution of measured phase shifts, we average the phase shifts over the active region. These average phase shifts are plotted in Figure 3. The average phase shifts increase with the surface magnetic flux as the active region is developing. But it is difficult to see the signature of upward-moving magnetic flux through the solar interior directly from these averaged phase shifts. In § 3 we will discuss how to infer the upward-moving flux from the average phase shifts normalized to the surface value.

3. DETECTION OF EMERGING MAGNETIC FLUX IN THE SOLAR INTERIOR

The phase shift at each focal point measured in acoustic imaging is phase-change accumulated along the wave path relative to the quiet Sun. It includes the phase change at the boundaries of mode cavity and flux tubes. The measured phase

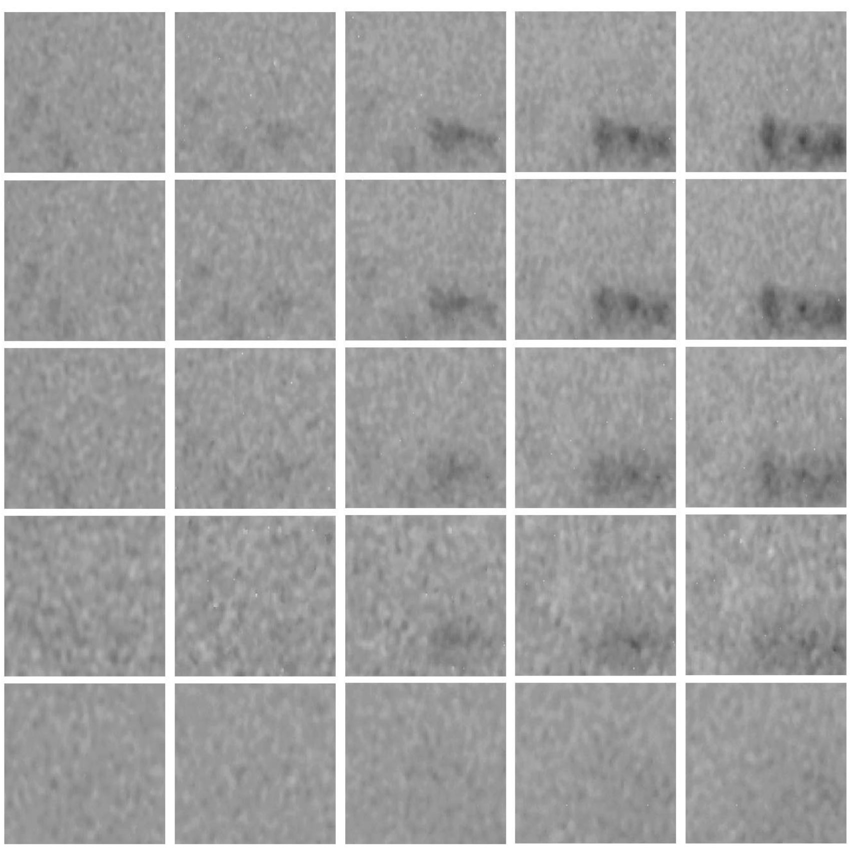

FIG. 2.—Phase-shift maps with 2 day temporal resolution from MDI data at 3 mHz. Columns from left to right correspond to 0705+0706, 0706+0707, 0707+0708, 0708+0709, and 0709+0710, where 0705 stands for 1996 July 5, and so forth. Rows from top to bottom correspond to focal depths at the surface of 10, 20, 30, and 40 Mm, respectively.

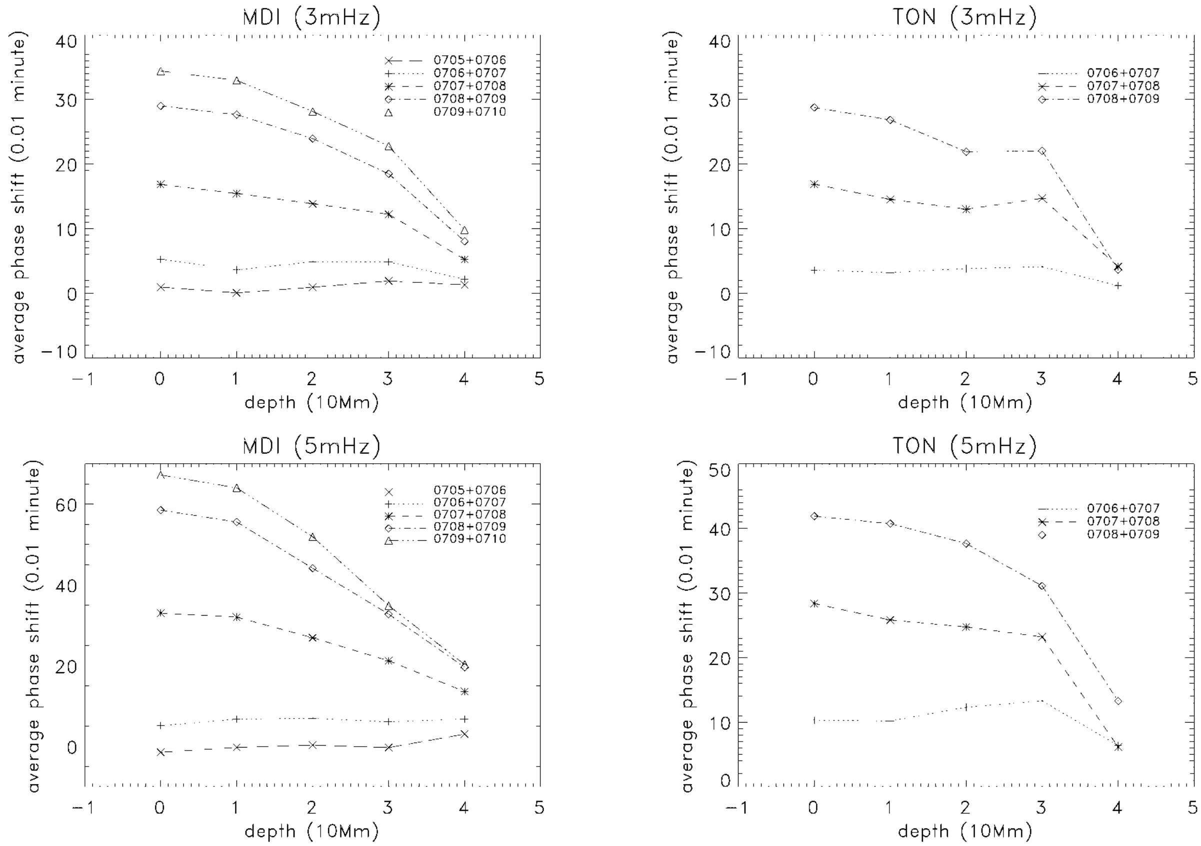

FIG. 3.—Average phase shifts over the active region as a function of depth for each data set

shift is the average effect of the local response of acoustic waves to magnetic fields along the wave path over all *p*-modes collected in the coherent summation. It also suffers from the wave property of *p*-modes. Thus, the measured phase shift does not directly represent the strength and structure of magnetic fields at the focal point. The combined effect of the wave property and the accumulated effect along the wave path can be represented by a kernel in an averaging integral.

An issue of great concern in acoustic imaging is whether features of magnetic regions seen in absorption and phase-shift maps at depths of 10 Mm or more are purely the leakage from the surface due to the wave property. If we assume an extreme case that the response of acoustic waves to magnetic fields is only significant at the surface, that is, absorption and phase shifts only occur at the surface, the measured average phase shifts below the surface will be entirely made up of the leakage from the surface. They will depend only on the surface magnetic field and the kernel. The depth dependence of measured average phase shifts normalized to the surface average phase shift reflects the depth dependence of the kernel. Thus, we expect for this extreme case that the depth dependence of normalized average phase shifts is the same at any time during which the flux is moving upward through the solar interior. The normalized phase shifts as a function of depth are shown in Figure 4. Although the shapes of the curves are different for different data sets, all four data sets show a similar time-dependent trend: the curves become steeper with time. The relatively stronger signals at deeper layers at earlier time indicate that the amount of flux is relatively larger at deeper layers at earlier time. This suggests that we are detecting the upward-moving magnetic flux through the solar interior during the development of the active region. However, the small variation in the slope of the curves suggests that a fairly large portion of the contribution to the measured phase shifts below the surface is the leakage from the surface due to the wave property.

The upward-moving flux can also be inferred from the average phase shifts normalized to the value at the same depth as the active region becomes stable. Again, such normalized phase shifts show enhancements at the deeper layers at earlier time. It corresponds to a larger amount of flux at deeper layers relative to the surface at earlier time.

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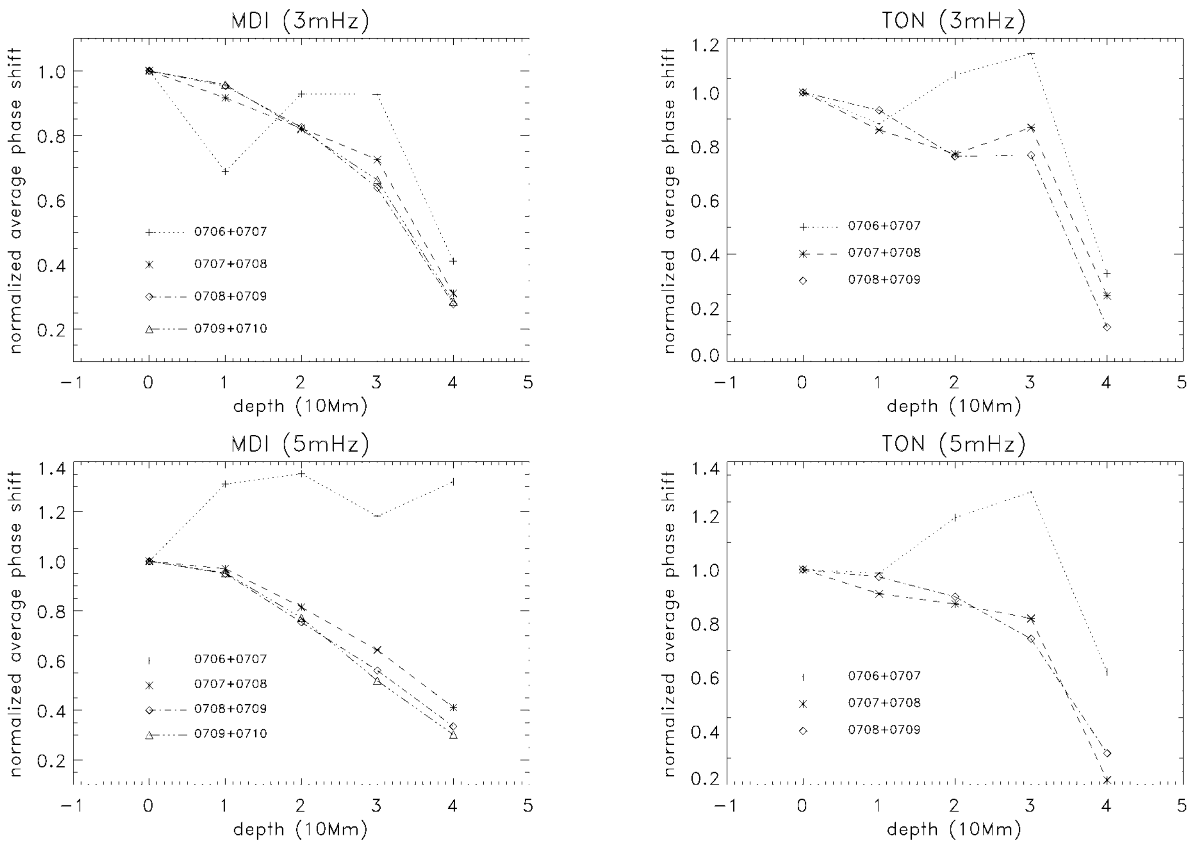

FIG. 4.—Average phase shifts normalized to the surface value as a function of depth for each data set

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